Peter S. Winokur, Chairman
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DEFENSE NUCLEAR FACILITIES SAFETY BOARD

Washington, DC 20004-2901

August 8, 2012

Mr. David Huizenga
Senior Advisor for Environmental Management
U.S. Department of Energy
1000 Independence Avenue, SW
Washington, DC 20585-0113

Dear Mr. Huizenga:

The staff of the Defense Nuclear Facilities Safety Board (Board) reviewed the design of the slurry transport system in the Pretreatment Facility of the Waste Treatment and Immobilization Plant (WTP) at the Hanford Site. The review focused on the nuclear safety evaluation of hazards and accidents related to pipeline plugging and engineering design considerations for the centrifugal slurry pumping systems. As a result of this effort, the Board is concerned that the design of the WTP slurry transport system has a substantial number of safety issues that require resolution.

The Board is also concerned about the lack of early integration of safety into the design of the slurry transport system. For example, the existing safety analysis does not address (1) the hazard of centrifugal pump explosions, and (2) the effect of erosion from a bed of sliding solids on pipeline wear analyses, including the corresponding reduction in pipe strength. The Board also observed that the project has been slow to incorporate new information on waste properties into the slurry transport system design. For example, the project has not incorporated reported data on the particle size and density of Hanford waste particles. These data include a Pacific Northwest National Laboratory report on Hanford waste physical and rheological properties and reports on the transfer of plutonium oxide particles from the Plutonium Finishing Plant to the Hanford tank farms. Incorporation of these data can lead to greater projected rates of erosion and a greater potential for pipeline plugging than currently considered in the WTP design basis.

Therefore, pursuant to 42 U.S.C. § 2286b(d), the Board requests a report within 90 days of receipt of this letter outlining actions DOE has taken or plans to take to address the issues related to deficiencies in the safety analysis and the design of the WTP slurry transport system summarized above and discussed in the enclosed report.

Sincerely,

Peter S. Winokur, Ph.D.
Chairman

Enclosure

c: Mrs. Mari-Jo Campagnone

DEFENSE NUCLEAR FACILITIES SAFETY BOARD

Staff Issue Report

June 1, 2012

MEMORANDUM FOR:	T. J. Dwyer, Technical Director
COPIES:	Board Members
FROM:	R. V. Kazban, A. P. Poloski, and S. A. Stokes
SUBJECT:	Plugging of Process Lines, Pretreatment Facility, Waste Treatment and Immobilization Plant, Hanford Site

This report documents a review by the staff of the Defense Nuclear Facilities Safety Board (Board) of the design of the slurry transport system in the Pretreatment Facility (PTF) of the Waste Treatment and Immobilization Plant (WTP) at the Hanford Site. The Board's staff conducted the onsite review during October 25–26, 2011, with representatives of the Department of Energy-Office of River Protection (DOE-ORP) and the WTP contractors, Bechtel National, Incorporated (BNI) and URS Corporation. Based on the results of the onsite review, the staff concluded that the design of the WTP slurry transport system had a substantial number of specific safety issues. Therefore, to determine what actions DOE-ORP and the WTP contractors took towards resolving these safety issues following the initial review, the Board's staff held a follow-up teleconference on May 8, 2012.

Background. The high-level waste slurries to be processed in PTF vary widely in their rheological properties, from Newtonian to Bingham plastic fluids, a type of non-Newtonian fluid with a semisolid structure. When designing a slurry pipeline, engineers typically establish a requirement for the minimum transport velocity, often called critical velocity. Critical velocity is defined as the mean flow velocity needed to prevent the accumulation of a layer of stationary or sliding particles on the bottom of the pipe (i.e., the pipe invert). Critical velocity is a crucial design parameter because it is undesirable to operate with a bed of particles that partially block the pipeline and can lead to increased pipe wear. Partial blockage also leads to increased head losses and fluctuating flow conditions, potentially resulting in a plugged process pipeline (Crowe, 2005). In addition to particle deposition mechanisms, other plugging mechanisms exist at WTP, including chemical plugging through formation of gels and precipitates due to changes in temperature, pH, and unintended chemical reactions (External Flowsheet Review Team, 2006).

Staff Issue. The PTF design strategy, which addresses plugging of process lines due to settling of solids, is to minimize the likelihood of plugging by implementing several design guides written by BNI. BNI uses these design guides to determine the critical velocity, pressure drop, and flush requirements for each process line in PTF. For process lines that transfer Newtonian slurries, the design guides state that flow in these pipelines should be turbulent and exceed an empirical prediction of critical velocity. These requirements prevent formation of a bed of sliding solids on the pipe invert. For process lines that transfer non-Newtonian slurries, the design guides rely on pressure drop and line slope requirements and do not impose critical velocity or turbulent flow criteria. This design strategy does not preclude a bed of sliding solids from forming in process lines that transfer non-Newtonian slurries. Furthermore, BNI engineers expect formation of sliding beds in some process lines. *However, the existing WTP erosion/corrosion allowances for piping assume that fluid velocity remains above the critical velocity, and sliding beds do not form.* The PTF design strategy also includes a requirement that each transfer of a Newtonian or non-Newtonian slurry is followed by a flush with water to minimize the likelihood of plugging. The design guides also provide a methodology to establish minimum flush volume and velocity for post-transfer flushes. Currently, the WTP design does not have a capability to obtain representative waste samples and, therefore, has only a limited ability to prevent material outside of the design basis from being present in the WTP process lines (Defense Nuclear Facilities Safety Board, 2010). Therefore, the high-level waste properties used to develop critical velocity and line flush requirements must be properly justified as bounding.

Observations. The staff reviewed the following elements of the PTF slurry transport system design bases: (1) the nuclear safety evaluation of hazards and accidents related to pipeline plugging; and (2) engineering design considerations for the centrifugal slurry pumping systems. Specific observations resulting from the review are detailed below.

Preliminary Documented Safety Analysis Deficiencies—The staff reviewed the Preliminary Documented Safety Analysis for PTF (Hinckley, 2011) and identified several safety issues. Specifically, the staff observed that BNI has not performed accident analyses for energetic releases due to pump explosions and fragmentation that would lead to a loss of primary confinement. This accident can occur when a centrifugal pump is operated for a prolonged period during a loss of flow. The loss of flow can be initiated by pipeline plugging (either chemical plugging or due to settling) or valve misalignment, which causes the contained solution to heat up and vaporize, resulting in pump over pressurization. This accident is more energetic than the spills and spray releases associated with pipeline breaches currently considered in the safety analysis and poses additional hazards from fragmentation to other structures, systems, and components. Centrifugal pump explosions have previously occurred at a defense nuclear facility (Gubanc, 1998), and are a recurring problem in the mining industry, where pumping slurries is a common activity. To address this safety issue, the Mine Safety and Health Administration (MSHA) has issued a bulletin (MSHA Program Information Bulletin P11-32) detailing safety controls that should be used to prevent this accident. BNI currently does not have such controls in the WTP design. During the onsite portion of the staff's review, the WTP project team agreed with the staff's observations regarding this issue and committed to complete a project issue evaluation report (i.e., PIER) and address this potential hazard in the planned updates to the hazard analysis for PTF. During the May 8, 2012, follow-up discussion, the staff determined that BNI has extended this evaluation to all WTP facilities, but made no progress in resolving this issue.

Design Deficiencies, Formation of Sliding Beds—The BNI design guide on minimum flow velocity for slurry lines consists of two major sections for use in determining (1) the critical pipeline velocity needed to prevent a bed of sliding solids from forming on the pipe invert and (2) the design of the flush system. BNI personnel stated that the design guidance for critical velocity applies only to Newtonian process lines with turbulent flow conditions; the guidance for flushing applies to both Newtonian and non-Newtonian process lines, in which each waste transfer is followed by a flush with water. BNI has provided no guidance for determining critical velocity in non-Newtonian process lines and, instead, relies on pressure drop and line slope requirements. The BNI design guide for process lines with Bingham plastic fluids provides a methodology to calculate the pressure drop for homogenous (non-settling) slurries and uses a decision criterion regarding the potential for solids settling based on particle size distribution and fluid properties. This decision criterion (i.e., the yield stability parameter) is valid in a stagnant fluid but is not appropriate to describe particle suspension when the fluid is sheared and particles are in motion relative to the fluid (Shook et al., 2002). BNI's criterion indicates that particles will not settle in the WTP process lines with non-Newtonian slurries, contrary to findings documented in Pacific Northwest National Laboratory (PNNL) reports (Poloski, 2009a, 2009b). The current design strategy will produce laminar flow in several non-Newtonian process lines (see Appendix A). Laminar flows of particle-laden Bingham plastic fluids do not have either turbulent eddies or a solid-like structure for complete suspension of large or dense particles, resulting in formation of a sliding bed of particles. Also, process lines thought to contain Newtonian slurries may instead contain non-Newtonian slurries during a pump transfer because of elevated concentrations of particles near the bottom of underpowered pulse-jet-mixed vessels (Winokur, 2012). Presently, the BNI design guides do not address this phenomenon.

Design Deficiencies, Erosion/Corrosion from Sliding Beds—The staff observed that the WTP project team has not evaluated the extent of erosion due to a sliding bed of particles. Therefore, the calculation to determine wear allowances for piping containing non-Newtonian fluids is incomplete (see Appendix B for details on abrasivity of WTP slurries). The presence of a sliding bed of particles in non-Newtonian process lines will lead to increased erosion/corrosion rates of the pipe invert and result in uneven pipe wear, with reduced pipe wall thickness at the invert location (Miller and Schmidt, 1984; Pagalthivarthi et al., 2009; Roco and Addie, 1987). BNI's analyses do not consider asymmetric wear patterns due to a sliding bed. Uneven wear patterns can also be shown to impact the stresses within the process piping (American Society of Mechanical Engineers, 2007).

Design Deficiencies, Use of Non-conservative Design Inputs—The staff observed that BNI is using several design bases to establish design requirements for various WTP systems that process the same particles. These design bases are not based on the latest Hanford tank waste characterization data. At the time of the staff's follow-up review, DOE-ORP had not directed the WTP project team to alter particle size and density in the design bases to include the latest data on the particle size and density of Hanford waste particles. These available data include:

- a recently issued PNNL report titled *Hanford Waste Physical and Rheological Properties: Data and Gaps* (PNNL-20646); and
- recently issued reports on the transfer of plutonium oxide particles from the Plutonium Finishing Plant to the Hanford tank farms titled *Historical Overview of Solids in PFP Aqueous Waste Transferred to Tank Farms: Quantity of Plutonium, Particle Size Distribution, and Particle Density* (24590-CM-HC4-W000-00176-T02-01-00001) and *Review of Plutonium Oxide Receipts into Hanford Tank Farms* (RPP-RPT-S0941, Rev. 0).

Instead, BNI is using a design basis from early characterization studies that consists of particle size distributions from a smaller set of tank waste characterization data. BNI analysts assume that the largest fraction of these particles is agglomerates and use an average agglomerate density to predict the critical velocity of the PTF pipelines. Results of PNNL tests (Poloski, 2009a, 2009b) indicate that use of an average density to describe the large particles is not conservative, and that particle density has a large influence on the overall critical velocity predicted by the correlation used in the BNI design guide. Further, high-density particles of moderate size are more challenging to transport and can form sliding beds more readily than large particles with a lower density.

Conclusions. The staff determined that the current design of the non-Newtonian WTP pipeline systems is susceptible to frequent formation of sliding beds on the pipe invert. Increased wear from erosion/corrosion at the pipe invert can occur if a pipeline with a sliding bed is operated. The presence of a sliding bed also can increase the likelihood that pipeline plugging events will occur. Chemical plugging is also a concern. Pipeline plugging events can lead to frequent plant shutdowns. Moreover, prolonged operation of a centrifugal pump with a plugged process line can cause the pump to overpressure and explode, resulting in the loss of primary confinement and damage to adjacent structures, systems, and components.

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Appendix A

Flow Regimes for Centrifugal Pumps at the Pretreatment Facility

The first step in determining a flow regime in the transport system for Bingham plastic fluids is to calculate the Hedstrom Number as follows (Hanks and Dadia, 1971):

$$He = \frac{D^2 \cdot \rho \cdot \tau}{\mu^2} \qquad \text{(A.1)}$$

where

He is the Hedstrom Number (dimensionless);
D is the pipe diameter (m);
ρ is the slurry density (kg/m^3);
τ is the slurry yield stress (Pa);
μ is the infinite shear viscosity (Pa·s).

The next step is to determine the transitional Reynolds Number, Re_t, that represents the transition from laminar-to-turbulent flow as follows (Poloski, 2009a):

$$Re_t = C_0 \left(1 + \sqrt{1 + \frac{He}{4500}} \right) \qquad \text{(A.2)}$$

where C_0 is a constant equal to 1,050 for the lower bound and 1,500 for the upper bound of the transitional flow region (i.e., $2100 < Re < 3000$ when $He = 0$).

The last step is to calculate the Reynolds Number based on the velocity of the fluid in the pipe, V, as follows (White, 1994):

$$Re = \frac{\rho \cdot V \cdot D}{\mu} \qquad \text{(A.3)}$$

Then, the obtained value of the Reynolds number is compared to the transitional Reynolds Number to establish the flow regime in the pipe (i.e., laminar, transitional, or turbulent).

Figures A-1 through A-3 below depict flow regimes for centrifugal pumps at the Pretreatment Facility (PTF) for transferring non-Newtonian slurries (Prado, 2011a, 2011b; Bauer, 2011). These figures show that the current design strategy for non-Newtonian pipelines at PTF will produce laminar or transitional flow in several non-Newtonian process lines, which may lead to pipeline plugging.

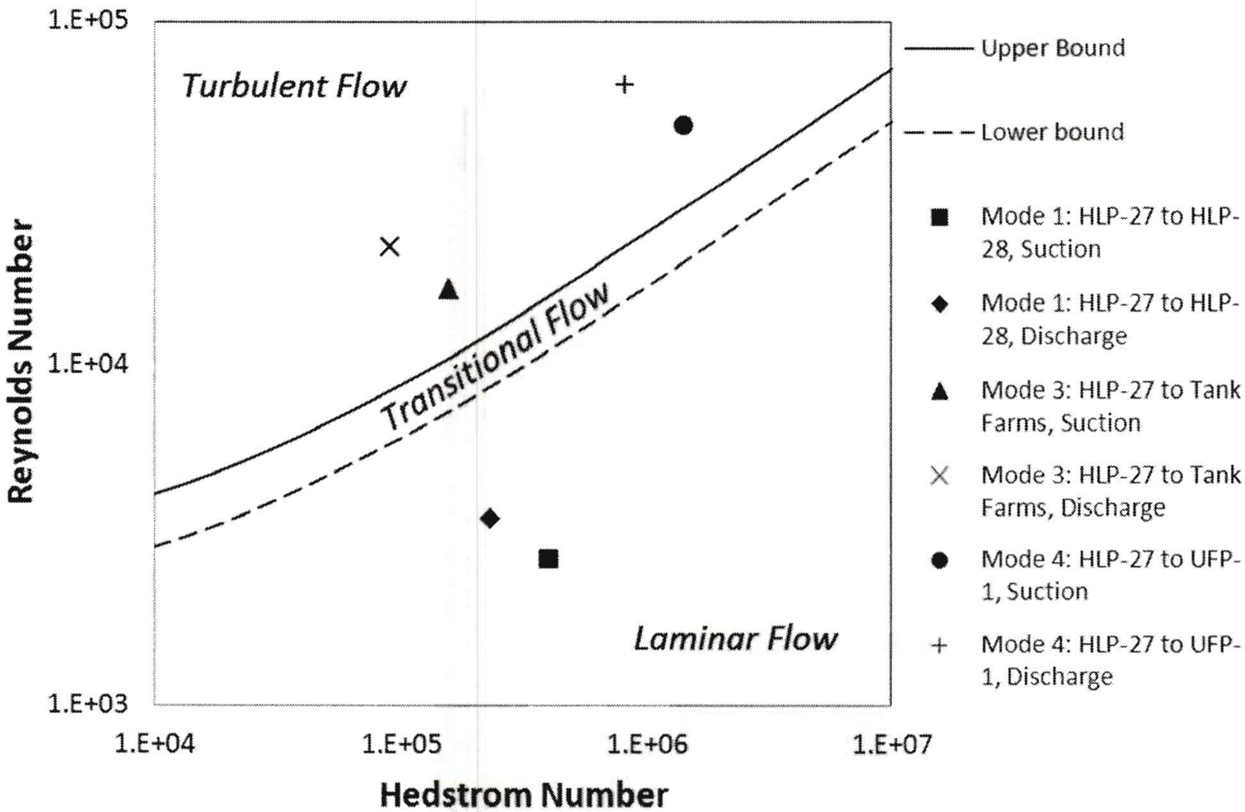

Figure A-1. Flow Regimes for Centrifugal Pumps HLP-PMP-00017A/B

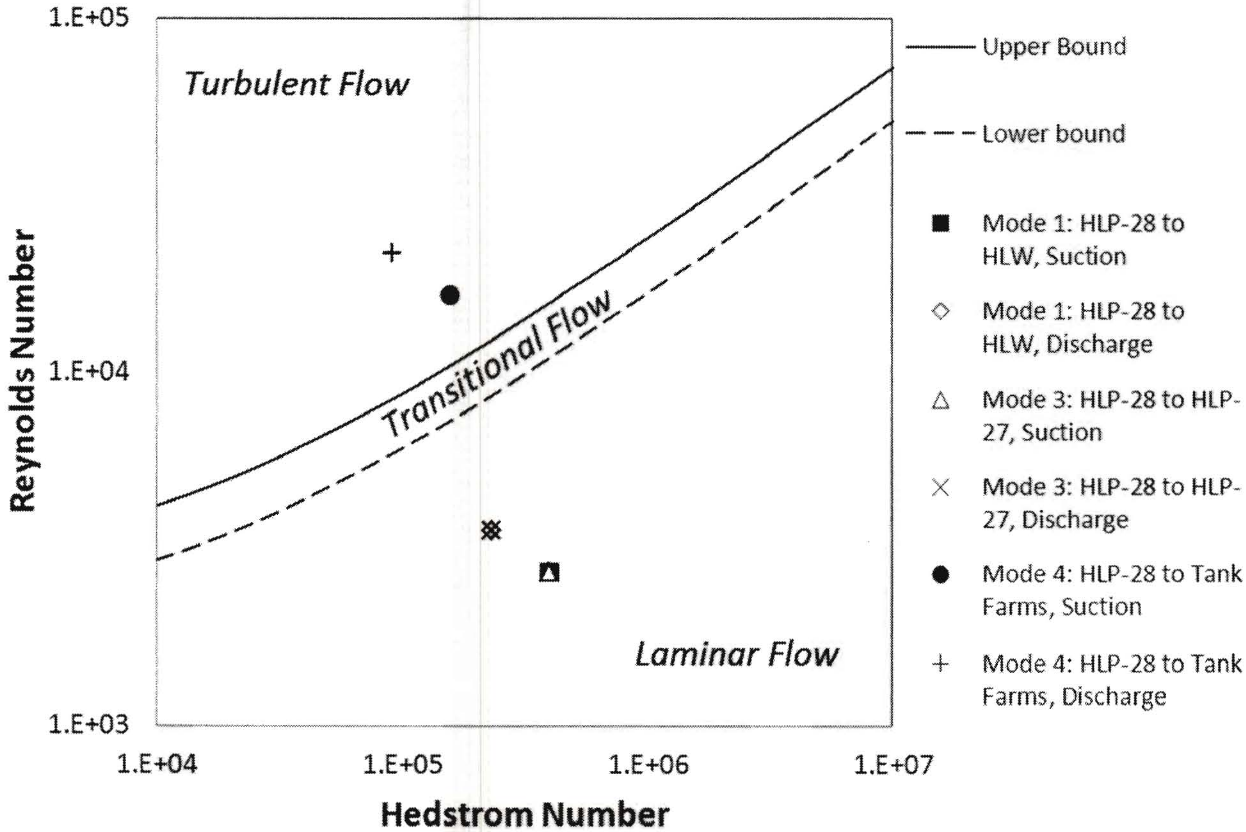

Figure A-2. Flow Regimes for Centrifugal Pumps HLP-PMP-00019A/B

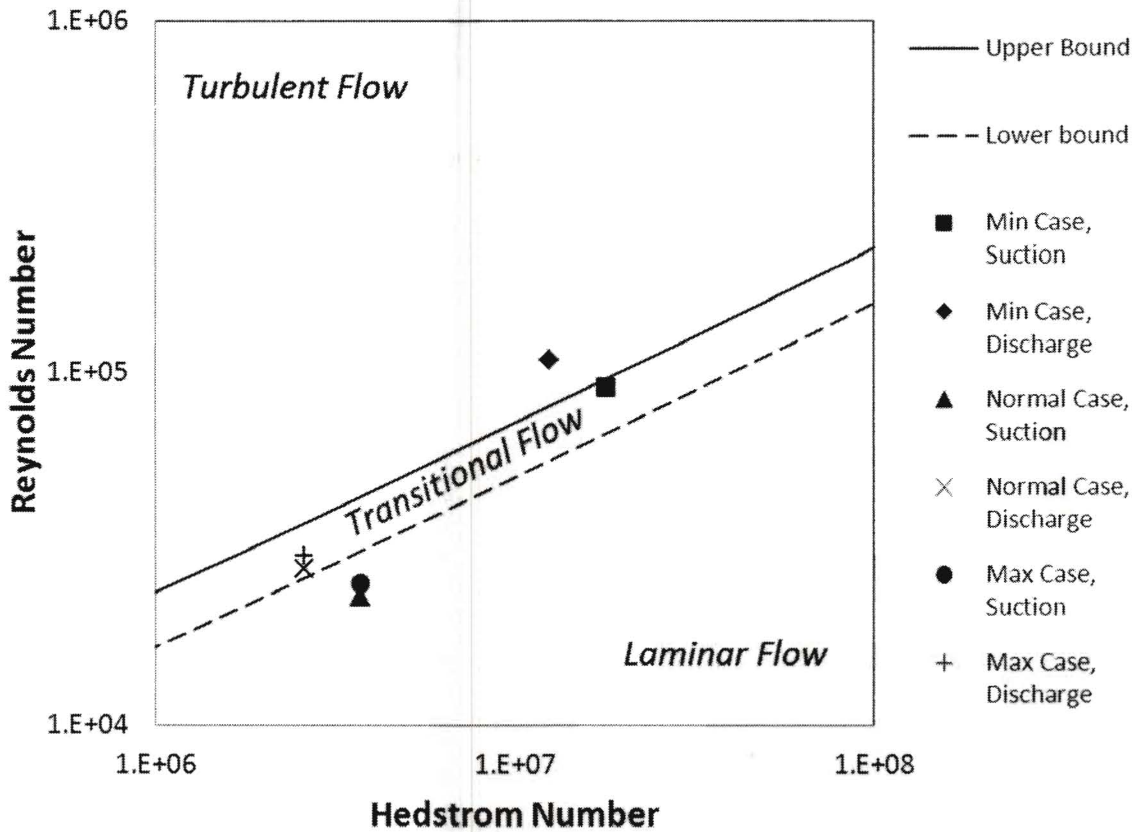

Figure A-3. Flow Regimes for Centrifugal Pumps UFP-PMP-00042A/B and UFP-PMP-00043A/B

Appendix B

Slurry Abrasivity Data for Actual and Simulated Hanford Wastes

Duignan (2002) produced seven WTP waste stream simulants and performed a standard abrasivity test per ASTM G75-01, *Standard Test Method for Determination of Slurry Abrasivity (Miller Number) and Slurry Abrasion Response of Materials (SAR Number)* (American Society for Testing and Materials, 2001), to determine a Slurry Abrasion Response (SAR) number for two types of stainless steel used by the WTP project, 304L and 316L. The ASTM G75 method uses a Miller number machine to determine the severity of abrasion-corrosion of the slurry on the wear materials by measuring the rate of mass loss from the material specimen and converting these data to a SAR number. During a test, a stainless steel wear block is attached to a reciprocating arm that slides the block at a controlled rate across a trough filled with slurry. Mass loss of the wear block occurs as the bottom of the block abrades from the sliding action of the block, slurry, and bottom of the trough. The ASTM method specifies that the bottom of the trough is made of a standard lap material, neoprene. The block is machined to dimensions specified by the standard and loaded with a total downward force of 22.24 N (5 lb). SAR number results from the seven simulated WTP slurries are shown in Figure B-1 along with a rating scale that shows regions of low to severe abrasion-corrosion. The results indicate that process chemistry, e.g., the addition of the submerged bed scrubber (SBS) solution, plays an important role in abrasion-corrosion of WTP process streams.

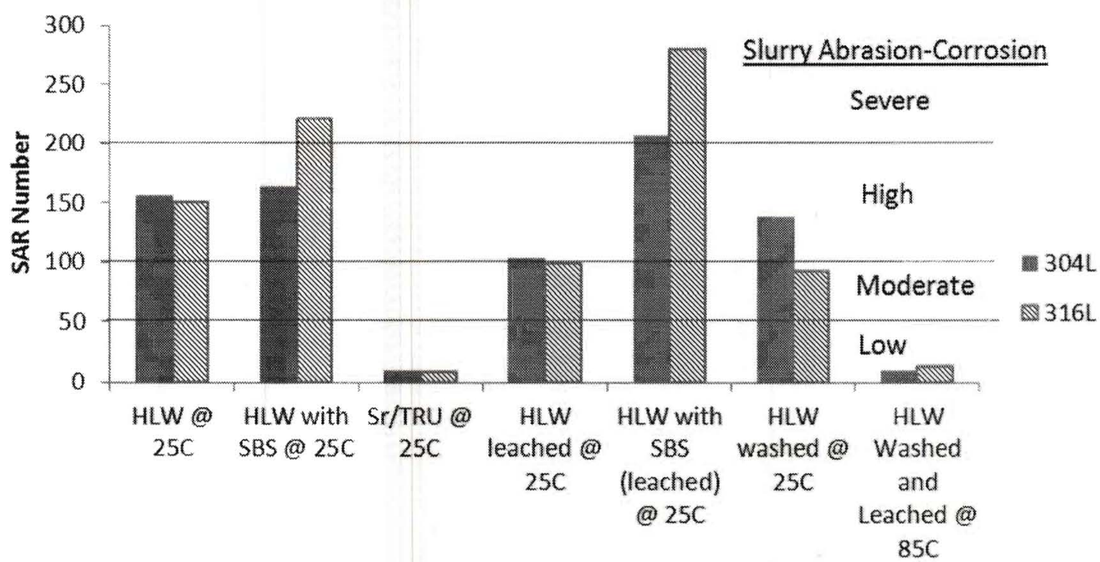

Figure B-1. SAR Number for Simulated WTP Process Streams

BNI's wear calculations assume that the stainless steel piping will experience little erosion at low flow velocities due to the small size and amount of hard waste particles. ASTM G75-07 (American Society for Testing and Materials, 2007) states:

> *"Experience has shown that slurries with a Miller Number or a SAR Number of approximately 50 or lower can be pumped with minor abrasive damage to the system. Above a number of 50, precautions must be observed and greater damage from abrasion*

is to be expected. Accordingly, the Miller Number and the SAR Number provide information about the slurry or the material that may be useful in the selection of pumps and other equipment and to predict the life expectancy of liquid-end parts of the pumps involved."

For sliding beds that are expected to occur in the WTP piping, abrasion-corrosion depends on the frictional force between the sliding bed and the pipe invert that is impacted by several key parameters such as the height of the sliding bed, particle and liquid densities, void fraction, and centrifugal forces from the bed moving through pipe elbows. BNI has not analyzed the specific conditions for abrasion-corrosion in WTP piping due to sliding beds of particles. The Board's staff found a large number of publications in the technical literature on the topic of wear rates in piping with sliding beds (e.g., Miller and Schmidt, 1984; Pagalthivarthi et al., 2009; Roco and Addie, 1987).

During a May 8, 2012, conference call, BNI stated that they do not consider the Duignan (2002) data to be significant because of the simulants used, i.e., approximately 7 wt% of the simulant solid consisted of tungsten oxide. BNI indicated that tungsten oxide is a very hard material that is not representative of the Hanford wastes. To the contrary, the simulant was developed by Pacific Northwest National Laboratory as documented in a report by Elmore (2000). Elmore provides the basis for selecting tungsten oxide and states:

"Hardness of the particles is an important parameter for abrasiveness, but there is no specific information on that property of the actual tank wastes. It is felt that uranium compounds in the waste could be rather hard particles, and may represent a significant fraction of the larger particles in the waste. Uranium minerals such as uraninite (UO_2) are not part of the waste simulants (despite representing 2 to 9 wt% of NCAW solids), because they are radioactive. Therefore, uranium minerals were simulated in this recipe by adding ~10 wt% tungsten oxide of an appropriate particle size distribution (See Table 1)."

Elmore then presents ASTM G75 test results for the simulant on three types of materials and compares them to a test result for actual Hanford waste from tank AZ-101 (Hodgson, 1995). The results shown in Table B-1 demonstrate that the simulant with tungsten oxide and the AZ-101 core sample both have "low" slurry abrasivity response with the 27 percent chromium-iron alloy. When the same simulant is tested with 316L stainless steel and C22 Hastelloy the slurry abrasivity response is categorized as "severe."

Table B-1. SAR Number for different Wear Materials

Slurry	*27% Cr-Fe Alloy*	*316L*	*C22 Hastelloy*
AZ-101 Core 3	8 (Low)	n/m	n/m
Simulated Waste Slurry	32 (Low)	431 (Severe)	405 (Severe)
n/m—not measured			